MODELLING CHEMISTRY AND ROCK ALTERATION IN THE DEEP HYDROTHERMAL SYSTEM FORMED BY A LARGE NEO-GRANITIC PLUTON

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SUMMARY In this paper we model a simplified hydrothermal mineral alteration assemblage for a generic, liquid dominated, geothermal field. The hydrothermal model of the field is based on the two-dimensional model of the Kakkonda field Mineral alteration is modelled using the simulator CHEM-TOUGH2. A comparison is made between the reservoir chemistry calculated with different permeabilities in the deep area of the reservoir.

1. Introduction

Magmatic intrusions are obvious candidates for the heat sources of geothermal fields. Perhaps the most thoroughly studied intrusion is that at the Kakkonda reservoir in Japan (Sasada et al. 1998). Although less well studied, a diorite intrusion was also intersected during the drilling of geothermal well NM4 in the Ngatamariki field, New Zealand. There is extensive hydrothermal alteration both within the intrusion and in a halo surrounding the intrusion which suggests it acted as a heat source for the convective hydrothermal system active at the time (Christenson et al. 1997,1998).

White and Christenson (1998) modelled the rock alteration about such an intrusion using the reactive transport simulator CHEM-TOUGH2 (White 1995). In this paper, we have applied this simulator to the Kakkonda system. The aim of the work is firstly to illustrate that it is indeed possible to reproduce the observed geochemistry and rock alteration in a geothennal field and secondly to investigate the use of chemical modelling to give insights into the conditions at depth, particularly the existence of permeability.

In the present study, we remove one of the major assumptions of White and Christenson, that of a single-phase reservoir. Here we include the effect of dissolved gases on saturation pressure and include the major gases (CO_2 and H_2S) as components in the gas and liquid phases.

2. Geothermal Convection System

As there is a large amount of published data on the Kakkonda field we have used this as a basis for a generic, liquid dominated, geothermal system. However it must be emphasized that the aim of this work is not to produce a realistic model of the Kakkonda field (and we do not claim to have done this), but rather to investigate the role of deep permeability on shallow (<2 km depth) chemistry and hydrothermal alteration.

The Kakkonda geothermal field is located about 600 km northeast of Tokyo and is one of the most active liquid-dominated fields in Japan. The history of production from the field and the hydrology of the production zones are described in some detail in McGuinness et al. (1994). The model used for this work is less detailed than that described by McGuinness et al. (1994) but represents the reservoir to a greater depth and is based on that presented by Hanano and Seth (1995).

Recent drilling at Kakkonda has found a large neo-granitic pluton of 0.34 to 0.07 Ma at a depth of 2000 - 2800 metres. Hanano and Seth (1995) modelled the convective geothermal system that developed about this intrusive. We repeat their work here including the chemical interaction between the reservoir fluid and reservoir rock and reactions between dissolved chemical species. We also allow the possibility of a gas phase containing CO_2, H_2S and *steam.*

A good summary of the current knowledge of the Kakkonda reservoir is contained in Sasada et al. (1998).

3. Conceptual model

Figure 1 shows the conceptual model of the modelled region and the boundary conditions used for the numerical simulations. In the simulations all boundaries apart from the top were impermeable, the side boundaries were insulating and the top and bottom boundaries were held at fixed temperature. The pressure at the top was fixed at 1 bar. Initially we assumed a linear temperature profile with 15" C at the surface and 500" C at the bottom, pressures were hydrostatic consistent with this temperature.

This temperature gradient is approximately twice the terrestrial average but is reasonable for an active region representing the effects of earlier magmatic intrusions. The area containing the intrusion was given a temperature of 800" C. At the surface we assume neutral (pH=7) water containing no dissolved solids or gases. Fluid throughout the rest of the reservoir is in equilibrium with the initial mineral assemblage in the reservoir. Initially the composition of the reservoir is that specified in Table 1

Table1: Initial rock composition.

Name	Composition	Weight %
Albite	$NaAlSi_3O_8$	40
Anorthite	$CaAl_2Si_2O_8$	40
K-Feldspar	$KAlSi_6O_8$	6
Quartz	SiO_2	14

In this initial model, we modelled the reservoir in terms of H_2O, H^+, Cl^-, SO_4^{--}, HCO_3^-, HS^-, SiO_2, Al^{+++}, Ca^{++}, K^+ and Na^+ component species These fluid components allow the modelling of reactions between the main magmatic volatiles (CO_2, SO_2, H_2S, HCl) and the most common rock-forming minerals (albite, anorthite, K-feldspar and quartz). Thirty-two of the most prevalent secondary aqueous species and twelve alteration minerals are also considered (alunite, anhydrite, calcite, kaolinite, muscovite, pyrophyllite, wairakite, sulfur).

Simplifying assumptions adopted in the treatment are:

- chemical equilibrium is maintained;
- the reacting minerals exert redox control on the system only via native sulfur
- reservoir permeability is isotropic (fracture flow is ignored).

We believe the assumption of chemical equilibrium to be justified in the hot area of the reservoir, but this assumption is certainly invalid in the cool areas. For example, the pH in the cool surface waters is much higher than normally found in shallow areas of geothermal reservoirs, but is correct for water in equilibrium with the assumed mineral assemblage at 15°C.

4. Chemical Environment

The hydrothermal environment within or immediately adjacent to shallow (< 4km) cooling plutons is characterised by high temperatures (up to 1100°C), pressures ranging from hydrostatic to lithostatic (ca. 200 – 2000 bar), and by the presence of highly reactive

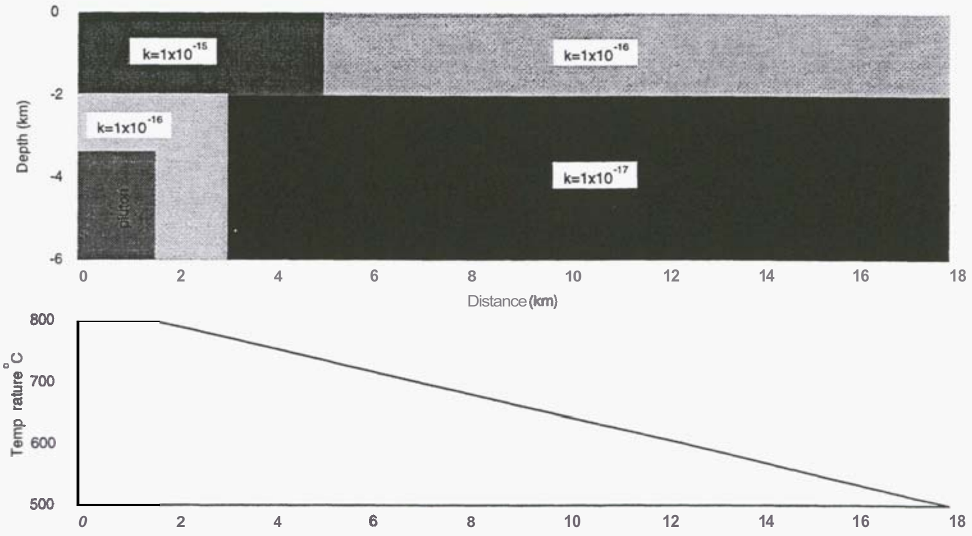

Figure 1: Grid and bottom temperature used for Kakkonda model

fluids. In this report, we have attempted to extend the earlier work of White and Christenson (1998) by including the pluton in the modelled area and allowing the volatile species to be released from the top of the pluton. ***The results near the pluton must be treated with caution*** as there is very little or no chemical data near the critical point.

The SOLTHERM database (Reed 1992) provides equilibrium constants as a function of temperature for all the reactions considered in this work up to a temperature of 350°C. It appears none of the widely available chemical databases provides data above this temperature explicitly. The program SUPCRT92 (Johnson ***et. al*** 1992) and associated databases provide a theoretical prediction of equilibrium constants for almost all the reactions of interest at higher temperatures (up to 415" C). There is excellent agreement between theoretical predictions of SUPCRT92 and the SOLTHERM database in regions where they overlap. In most cases there is still a gap in the data near the critical point of water. The approach we have taken is to use the SOLTHERM database where possible and the SPUPCRT92 values at higher temperatures. When the temperature exceeds 415°C we have used the 415°C values. Where data are missing near the critical point we have interpolated between temperatures below and above the critical point where data exist. In fact the chemistry at these high temperatures has almost no effect on the simulation as rock at these high temperatures is largely impermeable and the activity coefficients of charged aqueous species are very low.

5. Modelling Software

For this work we have used a version of TOUGH2 (Pruess 1991) that has been modified to include the transport of reacting chemicals (White 1995). The original code was capable of modelling temperatures up to 350°C and pressures up to 100 MPa. This has been extended to temperatures up to 800°C but the pressure limit of 100 MPa remains (White and Mroczek 1998).

We have ignored the solubility of all neutral aqueous species in the gas phase even though it may be significant between 360 - 374°C with pressures on the saturation line. Carbon dioxide and hydrogen sulfide gases are included in the simulation as is the effect they have on the saturation pressure of water.

6. Magmatic Intrusion

The fluxes of magmatic input into the convecting reservoir overlying the intrusion are based on those in White and Christenson (1998) (see Table 2). These gases, with an enthalpy of steam at 350°C, are injected into the model at the top of the pluton for a period of three years. After this the rate is dropped to 0.1% of the initial rate and the simulation run for up to *50,000* years.

Species	Initial rate (kg/s)	Long:term
H_2O	2.35	2.35×10^{-3}
H^+	2.06×10^{-2}	2.06×10^{-5}
Cl^-	3.82×10^{-2}	3.82×10^{-5}
$SO4^=$	1.98×10^{-1}	1.98×10^{-4}
HS^-	4.27×10^{-2}	4.27×10^{-5}
HCO_3^-	$9.23x10^{-4}$	9.23×10^{-6}

Table 2: Composition of magmatic gas.

7. Modelling Results

Two simulations were run, in the first (scenario 1) all permeabilities were as shown in Figure 1, in the second (scenario 2) the permeability of the region surrounding the pluton was reduced to 10^{-18} m^2 . All other parameters are the Same for both simulations. In particular it is assumed that the rate of outgassing is the same for both scenarios. However it could be argued that the rate would be reduced for scenario 2 as reservoir pressures immediately above the pluton are higher than in scenario 1.

Results of the modelling are summarised in Figures 2-5. The effect of low permeability around the intrusion can be seen clearly in some of these figures. The convective system in scenario 1 reaches to the top of the pluton and transports the magmatic volatiles into shallower parts of the reservoir. The pH is much higher for scenario 1 than scenario 2 and Cl^- concentration is lower. In scenario 2 the convective system is limited to the high permeability area above 2km depth.

pH and Cl^- contours depict the shape of the convective upwelling over the intrusion. Hydrogen ions within the plume are consumed in hydrolysis reactions. K-feldspar has been largely dissolved in the upflow and is replaced by muscovite, which in turn is replaced by kaolinite along the front of advancing acidic fluids. Ca^{++} released from the increased dissolution of anorthite is taken up in anhydrite in the low pH zone close to the heat source, and calcite further away. Fluids close to the source are most acidic, with concentration and the distribution of some of the alteration products throughout the reservoir.

8. Discussion

We have demonstrated that it is possible, with the assumptions given earlier, to model the chemical changes that take place in a geothermal reservoir in response to the degassing of a magmatic intrusion The

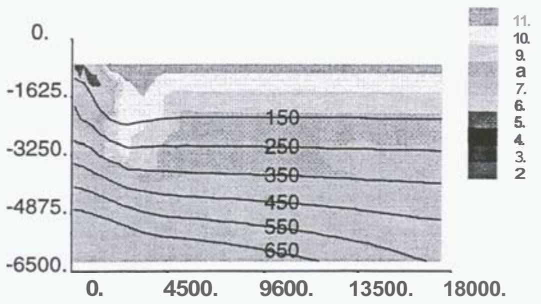

Figure 2(a) Calculated pH for scenario 1, solid lines are temperature contours in °C

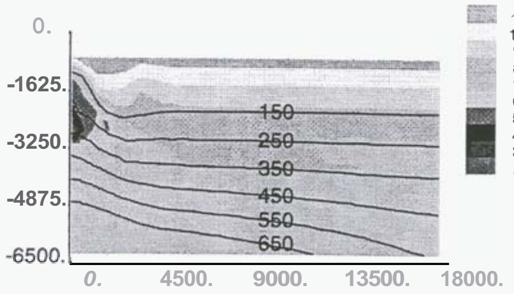

Figure 2(b) Calculated pH for scenario 2, solid lines are temperature contours in °C

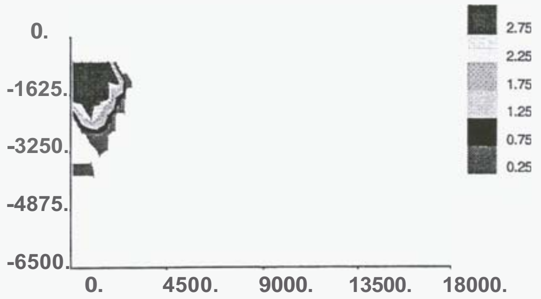

Figure 3(a) Calculated calcite for scenario 1, units are moles/dm^3 of fluid

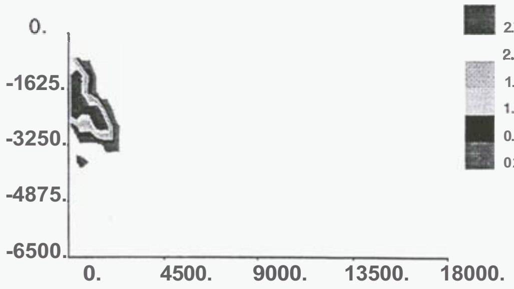

Figure 3(a) Calculated calcite for scenario 2, units are moles/dm^3 of fluid

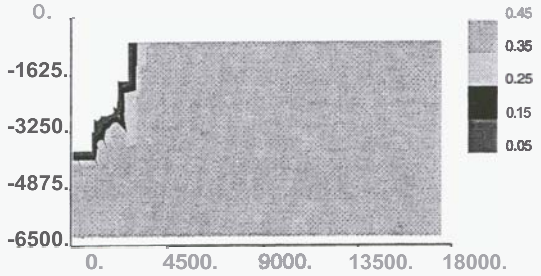

Figure 4(a) Calculated K-feldspar for scenario 1, units are moles/dm^3 of fluid

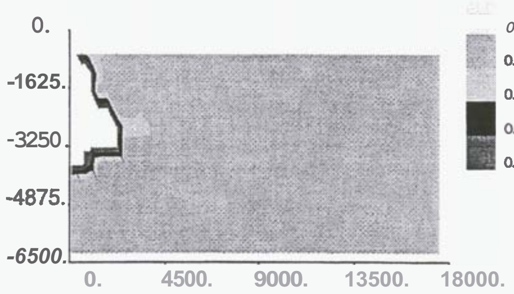

Figure 4(b) Calculated K-feldspar for scenario 2, units are moles/dm^3 of fluid

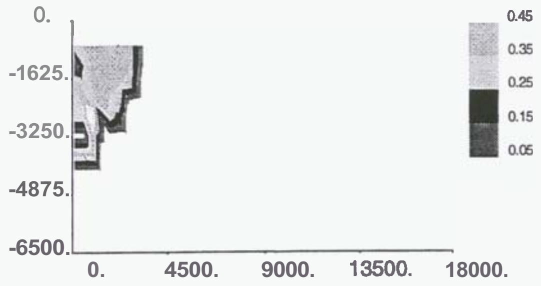

Figure 5(a) Calculated muscovite for scenario 1, units are moles/dm^3 of fluid

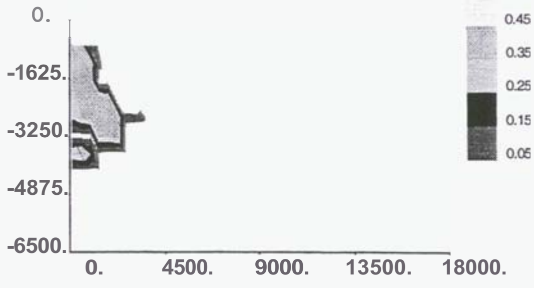

Figure 5(b) Calculated muscovite for scenario 1, units are moles/dm^3 of fluid chemical modelling includes sufficient detail to represent the processes associated with the neutralization of the low pH fluids that result fiom the dissolution of magmatic vapor into reservoir fluid and the hydrothed alteration taking place at intermediate and shallow areas of the reservoir.

Differences are apparent between the two scenarios modelled, which suggest observed shallow chemistry may be used as an indicator of deep processes. Shallow areas of rock alteration are more extensive when the permeable path extends between the near surface environment and the magmatic intrusion. This effect may be greater than shown by this modelling as we have assumed a constant rate of release of magmatic volatiles for both scenarios. In reality degassing of magma is described by a 'Henry's law' relationship and so one might expect a constant pressure of volatiles rather than a constant rate of release. This would further decrease the passage of aggressive fluids to the shallow areas of the reservoir and thus give less extensive hydrothermal alteration in this area.

9. References

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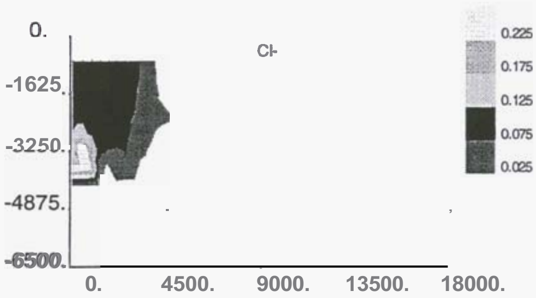

Figure 6(a) Calculated Cl^- for scenario 1, units are moles/dm^3 of fluid

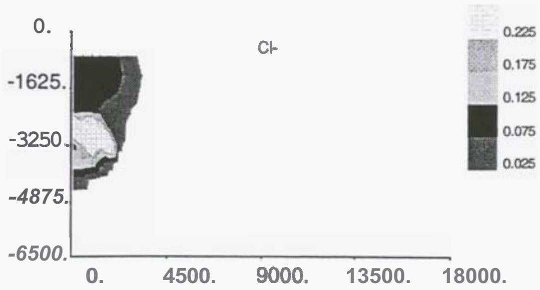

Figure 6(a) Calculated Cl^- for scenario 2, units are moles/dm^3 of fluid